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DEVELOPMENT AND PERFORMANCE EVALUATION OF AN ECONOMIC SOLAR GRAIN DRYER

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ABSTRACT

The development and performance evaluation of a solar dryer for the preservation of agricultural products such as groundnut seeds is presented in this study. The dryer is designed and constructed using locally available materials such as plywood, translucent glass, wood, paints, and wire-mesh. The performance evaluation of the dryer revealed that the optimum temperature of the dryer during the test period is 59°C with a corresponding ambient temperature of 31°C. An average dryer relative humidity of 48.05% and average temperature of 58°C was observed for the dryer during the drying days. This dryer will be usable by rural farmers in preserving seeds from wastage due to the rapid rate of drying.

Key words: Solar grain dryer, performance evaluation, relative humidity, ambient temperature, dryer work

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1. INTRODUCTION

The period of significant over abundance of farm produce which cannot be stored for long periods is the harvest time [1]. Due to this over abundance, there are wastages of the harvested farm produce. In Asia-Pacific region and including Africa, farm produce wastages abound and these are generally due to poor infrastructural preservation and processing facilities [2]. It is important to preserve harvested farm produce in an efficient and inexpensive manner. Hedge et al. [3] highlighted various methods of food preservation which are drying, freezing, salting, smoking, canning, refrigeration and bottling. Amongst all these preservation methods, drying takes larger percentage in food preservation.

Garg & Prakash [4] defined drying as a method of dehydration of food products which involves reducing the moisture content from the food to improve its shelf life by preventing bacterial growth. Moisture removal is important because moisture promotes disease, decay and degradation. Therefore, drying is needed to preserve grain quality. It is economical to dry under direct sunlight; however, lower quality of products would be obtained due to contaminations such as rain, pets, birds, dust and insects. Furthermore, the implications of the direct exposure of sunlight (traditional drying) which have ultraviolet rays on the farm produce are loss of vitamins and nutrient and unacceptable change in colour [5-7].

Solar drying, considered as the simplest and least expensive method, is readily available for preservation. However, the usage of this drying technique is underutilized [1]. In order to reduce postharvest losses and overcome shortages in supply, highly effective and practical means of preservation such as solar drying can be employed. To prevent vitamins and nutrients losses, and low quality due to contaminants; specialized devices that can be utilized in the control of the drying process and protect agricultural products are needed which include the solar dryers. Solar drying is a method that uses the heat energy from the Sun for drying, but excludes open air sun drying (traditional drying). Solar drying of crop is environmentally friendly and economically viable in the developing countries [8-9]. Three types of solar dryers are discovered such as solar natural dryers, semi-artificial dryers and solar-assisted dryers and are classified according to the type of energy used [10]. Solar dryer as classified by Hii et al. [5] can be based on their heating modes and the manner in which the solar heat is utilized. These are namely; forced air circulation or active solar dryers and natural air circulation or passive solar dryers. Active solar techniques include the use of photovoltaic panels and solar thermal collectors to harness the energy. Passive solar techniques include orienting a building to the sun, selecting materials with favourable thermal mass or light dispersing properties, and designing spaces that naturally circulate air. Based on the dryer working principle, drying mode and type of products to be dried; three distinct sub-classes of either the active or passive solar drying system exist, namely integral or direct mode, distributed or indirect mode and mixed mode solar dryers [11]. According to [1], a solar dryer should be fully operational in partially cloudy, hazy and sunny environments. An increase in the collector area increases the area available for insolation and therefore, the drying time is reduced.

The design of a solar grain dryer is a type of passive solar technique which uses the radiation of sun directly converted to heat with the aid of a carefully selected material of high thermal efficiency positioned to inclined at an angle of 15^0 towards the south over an enclosed insulated space large enough and well ventilated to ensure effective drying of farm produce. Michael & Ojha [12] stated that the general acceptability factor for grains is that it must be dried to moisture content not greater than its equilibrium moisture at 70% relative humidity and 27ºC (80ºF) temperature for long term storage. By utilizing solar energy, El-Shiatry, Muller & Muhblbauer [13] dried grapes, okra, tomato and onion. It was concluded through the results obtained that drying time reduced significantly which results in a higher product quality in terms of colour and reconstruction properties.

Umogbai & Iorter [14] made a comparison between sun drying (traditional drying) and solar drying when drying corn cobs. Results obtained show that the solar dryer generates higher temperatures, lower relative humidity, and lower product moisture content and reduced spoilage during the drying process than sun drying. Bolaji & Olalusi [7] developed and evaluated the performance of a mixed-mode solar dryer for food preservation. The results obtained revealed that the temperatures inside the dryer and solar collector were much higher than the ambient temperature during most hours of the day-light. It was concluded that the rapid rate of drying in the dryer reveals its ability to dry food items reasonably rapidly to a safe moisture level. A hybrid solar dryer was developed by [15] which employ direct solar energy and a heat exchanger. During normal sunny days, the dryer was operated as a solar dryer, and during cloudy days as a hybrid solar dryer. Moreover, with stored heat energy in water which was collected during the sunny time and with electric heaters, night drying was also carried out. The performance evaluation of the solar dryer was done by drying ripe banana slices. Several solar dryers for different agricultural products have been done by various researchers among which are hay dryer [16]; rough rice dryer [17]; fruit and vegetable dryer [18] banana dryer [19-20]; bamboo shoots dryer [21]; maize dryer [22]; tomatoes [23]; to mention but few.

An important leguminous crop found in the tropical and semi-arid tropical countries is groundnut. The term “Groundnut” refers to the pods with seeds that mature underground. On a global scale, groundnut is an oilseed crop and it is cultivated in as many as 90 countries [24]. It grows best in light textured sandy loam soils with neutral pH. In Africa, Nigeria is one of the major countries that are involved in the cultivation of groundnut. Therefore, groundnut seeds preservation after harvest is of utmost importance to rural farmers. Groundnut wastage is not an encouragement to rural farmers.

The drying time and drying temperature for groundnut seed drying to prevent wastages are important to be investigated and obtained using the developed solar dryer. The objective of this study is to develop an economic solar dryer for drying groundnut seeds using locally sourced materials. This will assist in determining the optimum temperature of the developed dryer, its corresponding ambient temperature and the mean dryer relative humidity. Moreover, drying rapid rate between the open sun drying and the developed solar dryer was examined through moisture losses. The groundnut seeds are dried simultaneously by both direct radiation through the transparent walls and roof of the cabinet and by the heated air from the solar collector. The solar dryer was designed to store solar energy so as to reduce the drying cost. The performance of the dryer was also evaluated. This economic solar grain dryer will assist in reducing wastage in the method of preserving grains with a cost effective means. This dryer will improve the quality and market value of the grains by preventing microbial growth and infections by insects, rodents, dirt, dust and flies on the grains.

1.1.Operating Principle

The solar dryer employs the principle of energy conversion in its operation. The rays of solar energy reflect directly on the glass collector and the glass becomes hot and transfer heat energy to the drying chamber through the absorber. Air flows in through the lower vent hole and get heated up laden with moisture evaporated from the drying grains and flows out of the chamber through the upper vent hole. The process continues in cycle and consequently moisture is evaporated out of the drying seeds.

2. EXPERIMENTAL SETUP

2.1. Description of the solar dryer

A solar dryer was designed, constructed and tested at the University of Ibadan, Oyo State, Nigeria (Latitude 7° 23' 28.19″ N; Longitude 3° 54' 59.99″ E). The solar dryer majorly consists of two units: solar collector and drying chamber. Fig. 1 illustrates the schematic view of the solar dryer.

2.1.1. The Solar Collector Unit

The solar energy collector is made of translucent glass of about 5 mm thick. The translucent glass is employed to reduce the amount of heat loss compare to the existing transparent glass used by former designer. The solar collector is inclined to angle 15° towards the south pole of the earth to increase the heating effect of the sun on the collector. The collector unit has an absorber which is made of metal sheet and is coated with black paint to increase its absorptiveness and hence increase the heating effect within the drying cabinet.

2.1.2. The Drying Chamber

The drying chamber is a rectangular box frame of an external dimension of $(700 \times 700 \times 900)\ mm$. In order to reduce the weight of the cabinet, the chamber is made of plywood and reinforced with strong wooden frame. For easy heat absorbance, the inner surface of the drying chamber is coated with black paint so as to increase the heating and drying effect of the chamber. The cabinet has a door which is for easy loading of grains to be dried in the dryer. The drying chamber access door of the dryer was satisfactorily done to fulfill [25] conditions. The drying chamber consists of the set of drying trays made of wood and stainless steel wire mesh. The drying trays were designed to be strong enough to withstand vigorous cleaning as well as the weight of products; have a material that will enable good circulation of air through the tray; a non-toxic material (use of galvanized or aluminium tray material be avoided); design to easily fit into the dryer and they are spaced $50\ mm$ apart. Vent holes were incorporated into the drying chamber for inflow and outflow of air into the cabinet. The vent holes were covered with wire mesh to prevent inflow of dust and other permissible destructive particles.

2.1.3. Detailed Construction Procedure for the Solar Dryer

The materials involved in the construction include thick plywood, translucent glass, angle hard wood (for skeleton), screws, wire mesh, black paint, and flat hardwood. A translucent glass was used as glazing surface to cover the top. The top glazing dimension was $710\ mm \times 700\ mm$. The plywood of dimension $700\ mm \times 700\ mm \times 19.05 mm$ was used in covering the base while the two sides were covered by a trapezoidal shaped plywood with the two lengths being $L1 = 700\ mm\ and\ L2 = 900\ mm$ and the length of the side being $700\ mm$. The door of the dryer was made of wood with the dimension $500\ mm \times 500\ mm$, while the opposite side of the door was covered by a $900\ mm \times 700\ mm \times 19.05\ mm$ plywood. The dryer frame was formed with the hardwood and raised $120\ mm$ above the ground level.

All the components were mounted on the frame and joined such that the various components are visible and can be likely disjointed for easy movement from one location to another. Provisions were made in the upper part for chimney and lower part air vents for proper air circulation, which will hasten the drying of the samples. The trays were separated with a gap of $200\ mm$. The trays were made of wire mesh and hardwood measuring $30\ mm \times 30\ mm$ high and the dimension is $680\ mm \times 680\ mm$. Figs. 2 - 5 show pictorial views of the solar dryer developed.

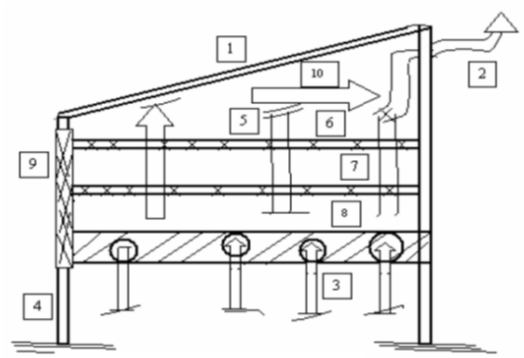

Fig 1 A Schematic diagram of the solar grain dryer

1. Translucent Top Glass cover
2. Chimney
3. Vent (Cold Air Inlet)
4. Hardwood Stand
5. Air Flow
6. Tray1 (made of Wire mesh)
7. Tray 2 (made of Wire Mesh)
8. Wooden Cover
9. Solar Dryer Door
10. Absorber Plate

(a) (b)

Fig 2 Overview of the Economic Solar Grain Dryer

Fig 3 Internal Views of the Solar Grain Dryer

Fig 4 Dryer Trays

Fig 5 Loading of Dryer

2.2. Design Calculation

2.2.1. Declination(δ)

This is the angle between the sun's direction and the equatorial plane and is given in Eq. (1):

$$\delta = 23.45\, sin\, [0.9863\, (284 + n)] \tag{1}$$

where n is the day in the year which varies from 1 to 365 [26]. The values obtained range between 22.108° and 22.698°.

2.2.2. Optimum collector slope (Ė):

The optimum collector slope, Ė, is determined from half of maximum slope of collector β, which is calculated using Eq. (2)

$$\beta = \delta + \varphi \tag{2}$$

where δ is the angle of declination for Ibadan, Nigeria and φ is the Latitude of the location (Ibadan, Oyo State, Nigeria, latitude 23' 28.19″N).

By calculation, the average of the daily maximum collector slope equals 29.634° using Eq. (3);

$$\bar{\beta} = \frac{\Sigma \beta}{N} \tag{3}$$

where $\bar{\beta}$ is the daily maximum collector slope permissible and N is the number of days for experimental test drying of the grain.

The optimum collector slope, Ė, can be calculated using Eq. (4):

$$\dot{E} = \bar{\beta}/2 \tag{4}$$

Therefore, the *optimum collector slope, Ė*, for the period equals *14.82º.*

2.2.3. Collector efficiency

This is computed from Eq. (5)

$$\eta = \frac{\rho V C_p \Delta T}{A I_c} \tag{5}$$

where ρ = density of air (kg/m^3), I_c = insulation constant of the collector, ΔT = temperature elevation, C_p = specific heat capacity of air at constant pressure (J/kg K), V = volumetric flow rate (m^3/s), and A = effective area of the collector facing the sun (m^2).

2.2.4. Dryer efficiency:

This is obtained using Eq. (6).

$$\eta_d = \frac{ML}{A I_c t} \tag{6}$$

Where L = the latent heat of vaporization of water, M = mass of the crop, I_c = insolation on the collector, A = effective area of the collector facing the sun (m^3), and t = the time of drying.

2.2.5. Rate of heat flow into the dryer:

This is the sum of the convective heat (Q_c), conductive heat (Q_k), and radiative heat transfers, (Q_r). This is given by Eqs. (7) and (8)

$$Q = Q_c + Q_k + Q_r \tag{7}$$

$$\frac{q}{A} = \frac{T_a - T_d}{\frac{1}{h_a} + \frac{\Delta x}{k} + \frac{1}{h_d}} + \varepsilon\sigma\left(T_a^4 - T_d^4\right) \tag{8}$$

where $\frac{q}{A}$ = rate of heat transfer per unit area, h_a= heat transfer coefficient for the ambient, h_d= heat transfer coefficient for the dryer chamber, T_a = ambient temperature, T_d = chamber temperature, σ = Stefan–Boltzman constant, Δx = thickness of the glass cover, A= effective area of the collector, ε= emissivity.

Heat energy (Q) needed for crop drying at moderate temperature is obtained using Eq. (9)

$$Q = M_w L = \rho C_p V (T_a - T_b) \tag{9}$$

where L = latent heat of vaporization of water, M_w = mass of crop before drying, ρ = density of water, T_a = ambient temperature, T_b = Dryer temperature.

2.3. Moisture loss ($\boldsymbol{M_l}$)

The Moisture loss is calculated using Eq. (10)

$$M_l = (M_i - M_f) \tag{10}$$

where M_i = the mass of the sample before drying, and M_f= the mass of the sample after.

2.4. Determination of percentage moisture content:

Percentage moisture content removed from a given quantity of wet grains in a specified time can be calculated using Eq. (11):

$$M_c = \frac{M_i - M_f}{M_i} \times 100\% \tag{11}$$

where: M_c= percentage moisture content removed, M_i = initial mass, and M_f = final mass.

2.3. Experimental testing procedure

Testing was performed from for five consecutive days at the University of Ibadan, Ibadan (Latitude 7° 23' 28.19″ N; Longitude 3° 54' 59.99″ E). Each test was conducted for five days to reduce the moisture from the samples. For comparison purpose, the groundnut seed was concurrently dried using the solar dryer and an open sun drying. The tests were carried out only on sunny days and the testing was repeated four times in a day for a length of five (5) days. The average air temperature and relative humidity were obtained during the testing period.

The solar dryer was set up in an outdoor environment which is to be compared with the traditional sun drying technique. Weight measurement was taken approximately every hour during the day, for which moisture loss and percentage moisture content were determined for both drying using the developed solar dryer and the traditional open sun drying.

3. RESULTS AND DISCUSSION

The product used in the testing of the dryer is groundnut of 1200 g. The average relative humidity of the environment is 48.05% and the maximum dryer temperature is 59ºC (318K).

3.1. Moisture loss with day time: Comparison of solar dryer and open sun drying

The solar dryer and open sun drying moisture losses were compared for the five days. The drying experiment was carried out between 10 am and 4 pm. Figs. 6-10 show that as the day time increases for all the days, the moisture loss from the groundnut seeds increases with both drying methods. However, the amount of moisture loss in the solar dryer when compared with the open sun drying is higher across all the days. This indicates that the solar dryer performed more efficiently than the open sun drying method. The high performance of the solar dryer can be attributed to heat absorbed by the drying chamber.

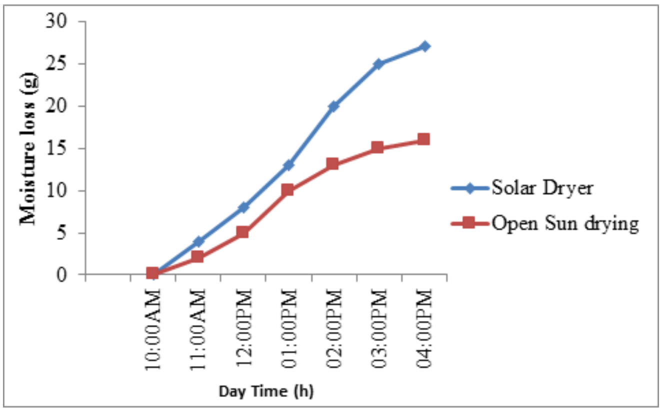

Fig 6 Moisture loss against day time for both Solar dryer and Open Sun drying on Day 1

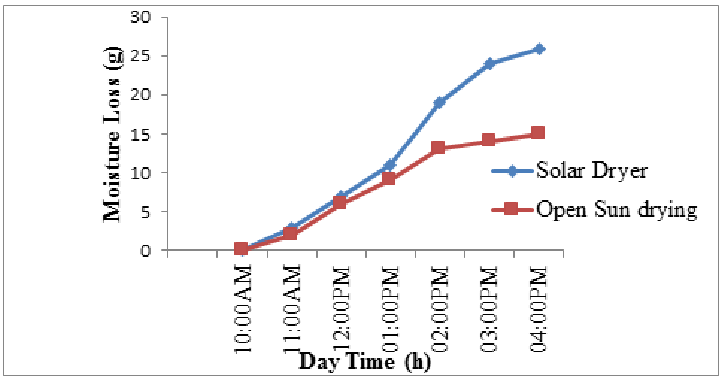

Fig. 7 Moisture loss against drying time for both Solar dryer and Open Sun drying on Day 2

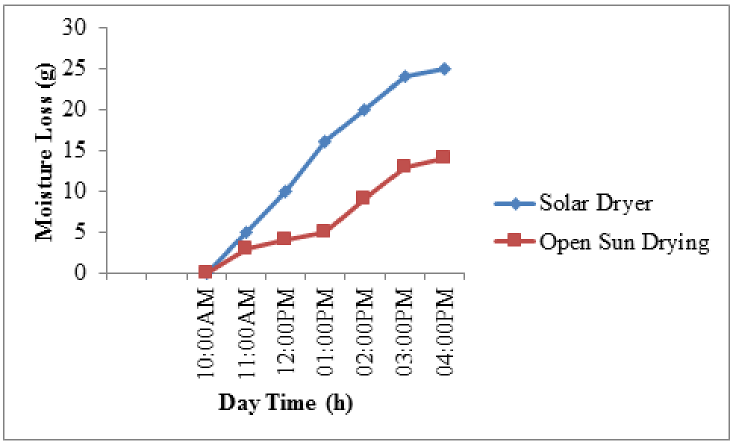

Fig.8 Moisture loss against day time for both Solar dryer and Open Sun drying on Day 3

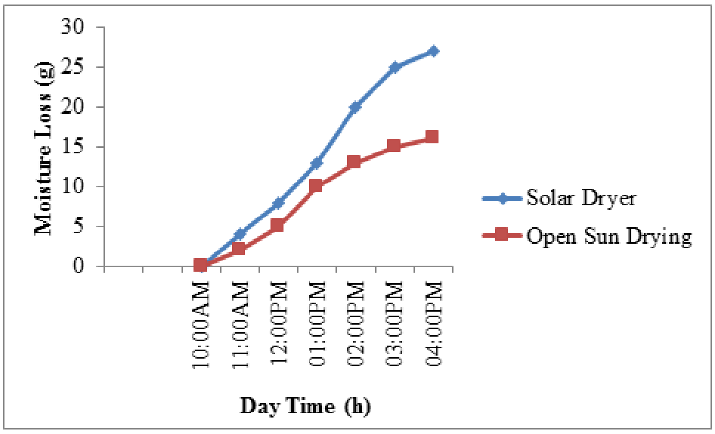

Fig 9 Moisture loss against day time for both Solar dryer and Open Sun drying on Day 4

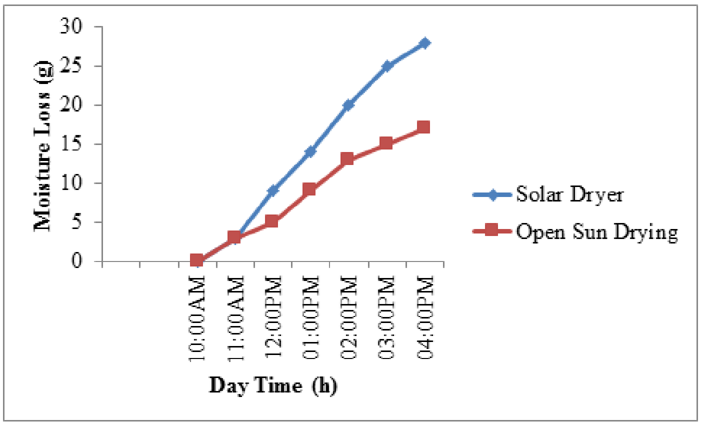

Fig 10 Moisture loss against day time for both Solar dryer and Open Sun drying on Day 5

3.2. Percentage moisture content with day time: Comparison of solar dryer and open sun drying

Percentage moisture content of both drying techniques reduces as the day time increases as presented in Figs. 11-15. It was observed that the groundnut seeds when dried using the developed solar dryer gives better percentage moisture content than the open sun drying method. The percentage moisture content for the solar dryer and open sun drying were compared. The range of percentage moisture content for solar dryer was 12-15% while for the open sun drying was 23-26% after the experimental days. It was reported by [15] that for solar and sun drying of banana slices, moisture content of the banana slices using the solar dryer was lower than the dried slices by the sun drying. This is in agreement with this study as the groundnut seeds percentage moisture content when dried in solar dryer was lower than what is obtainable for open sun drying. The values obtained for the solar dryer indicate that the product shelf life for preservation is guaranteed, thus putting an end to wastages. This indicates that when it comes to drying and moisture removal from groundnut seeds, the solar dryer is better to be utilized.

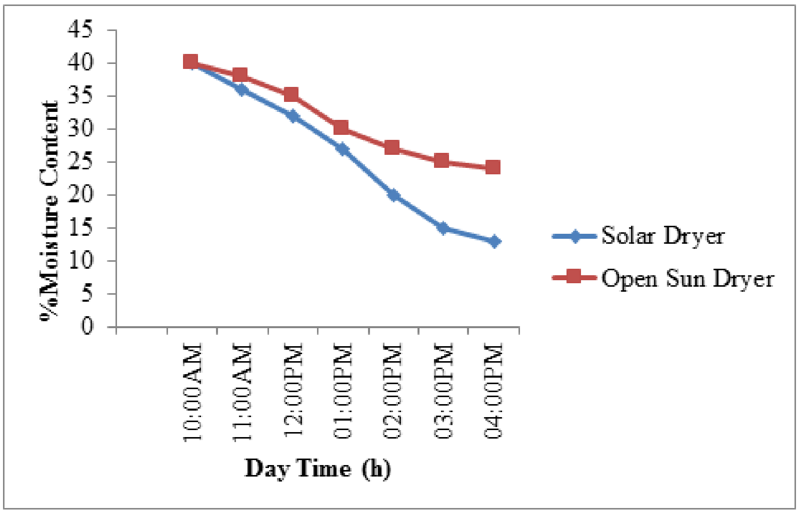

Fig 11 Percentage moisture content against day time for both Solar dryer and Open Sun drying on Day 1

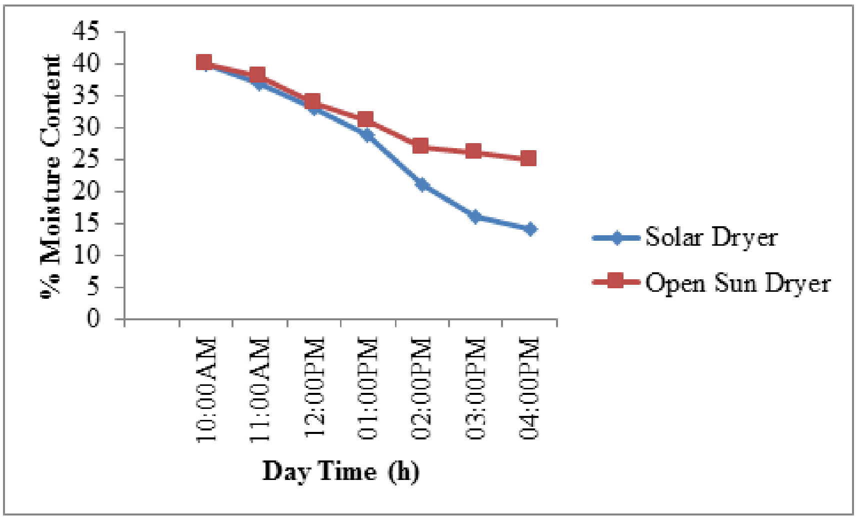

Fig 12 Percentage moisture content against day time for both Solar dryer and Open Sun drying on Day 2

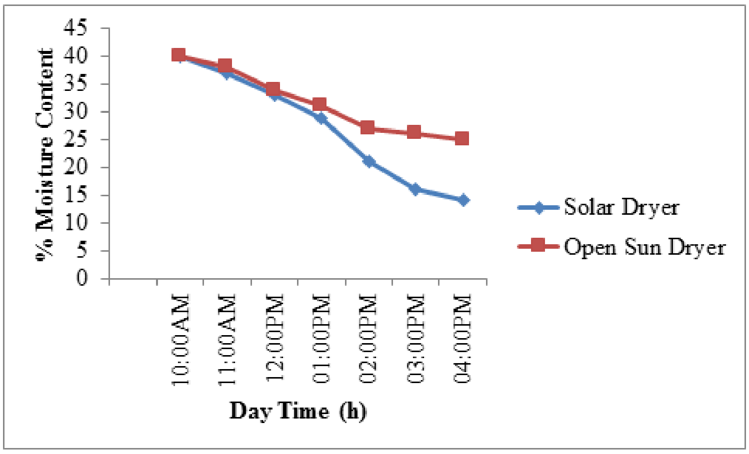

Fig 13 Percentage moisture content against day time for both Solar dryer and Open Sun drying on Day 3

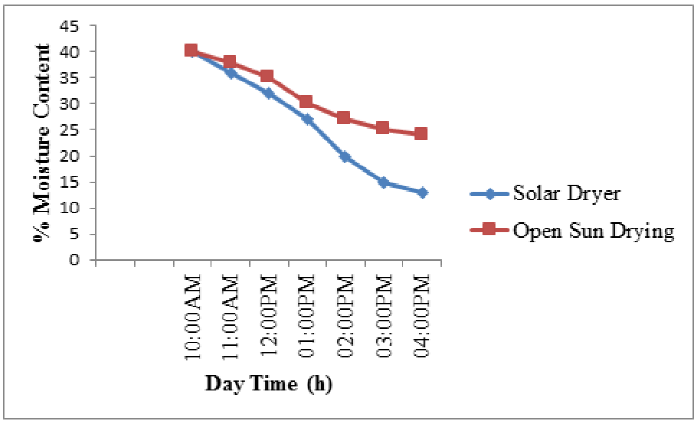

Fig 14 Percentage moisture content against day time for both Solar dryer and Open Sun drying on Day 4

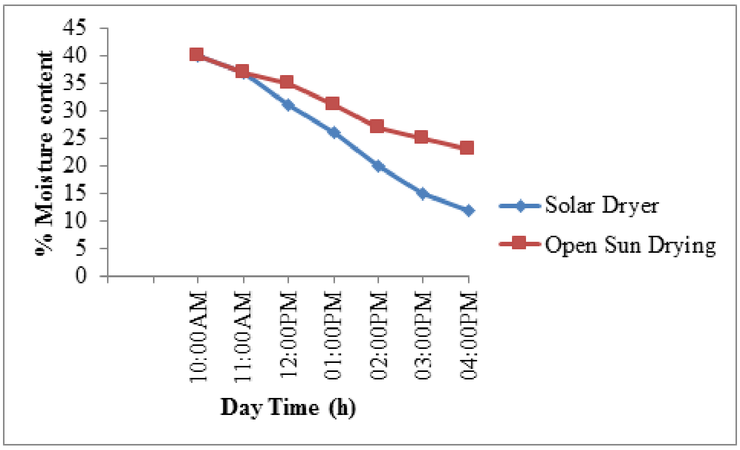

Fig. 15 Percentage moisture content against day time for both Solar dryer and Open Sun drying on day 5

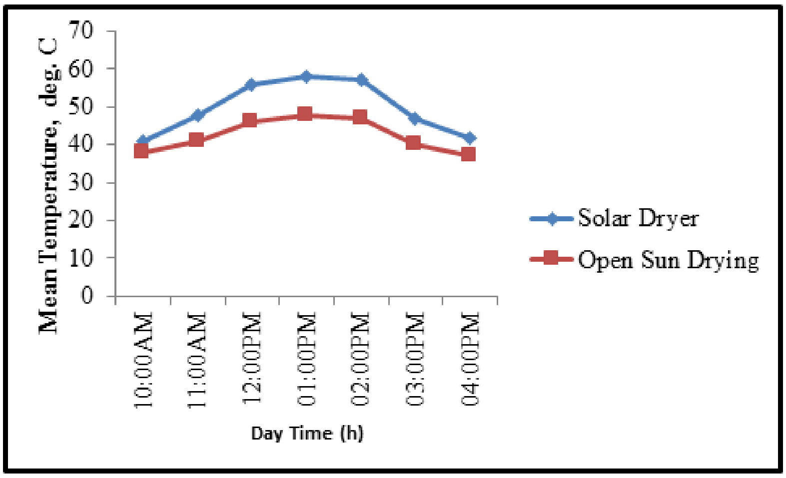

Fig 16 Mean Temperature against day time for both Solar dryer and Open Sun drying

The hourly variation of the mean temperature in the drying cabinet and in open sun drying with the day time is as shown in Fig. 16. It was observed that as the day time increases, the temperature also increases until a peak value is reached between 1pm and 2pm. A gradual decline was noticed immediately after the peak range was reached. The temperature increase is due to increase in solar radiation and the decline is due to the gradual decrease of the solar radiation [15]. Moreover, this supports the studies of [3] and [27] where solar radiation is mostly at peak around 1pm. Therefore, as solar radiation increases the temperature also increases. For the solar dryer, at the peak day time, the temperature was 58°C and for the open sun drying, the peak temperature was 48°C around 1pm. The temperature difference of 10°C between the solar dryer and the open sun drying can be attributed to the amount of heat energy absorbed by the dryer in its enclosed cabinet and radiated for the drying purpose.

Fig.17 shows the comparison done between the percentage mean moisture content of the groundnut when dried using solar dryer and open sun drying. Using both methods, moisture content reduces while the day time increases. The amount of moisture removed from the groundnut by the solar dryer is higher than that of the open sun drying. It implies that the drying rate of solar dryer is faster than that of the open sun drying. Furthermore, solar dryer generate higher temperatures with rapid rate of drying food to a safe moisture level and reduce spoilage during the drying process than sun drying [7, 14]

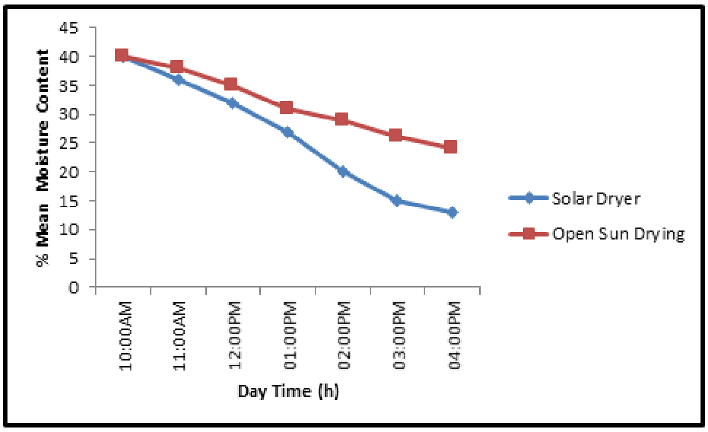

Fig 17 Mean Temperature against day time for both Solar dryer and Open Sun drying

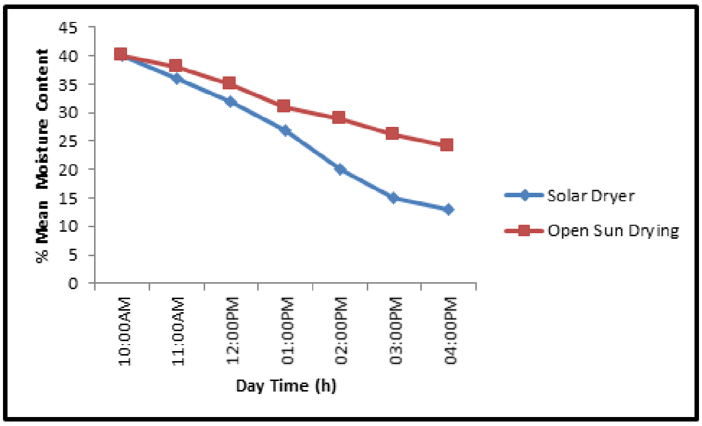

Fig 18 Mean Percentage moisture content versus mean temperature (ºC) for solar dryer

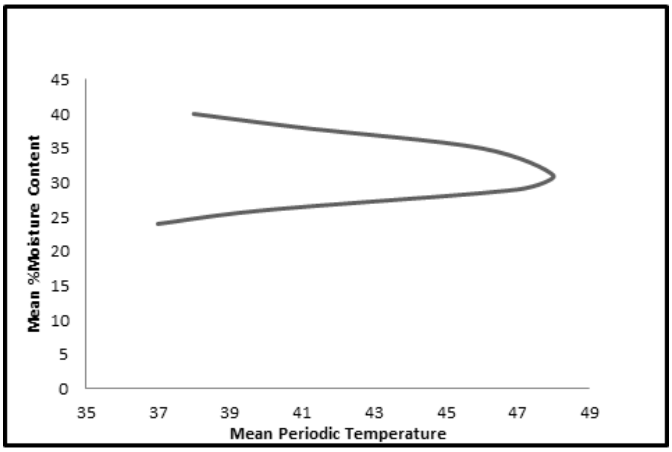

Fig 19 Mean Percentage moisture content versus mean temperature (ºC) for open sun drying

In the relationship between the mean percentage moisture content and the mean periodic temperature, increase in temperature increases the moisture content until a peak temperature is reached and a gradual decline is achieved as the temperature increases as presented in Figs. 18-19. At peak temperature 58ºC, the percentage mean moisture content is 27% for the solar dryer and at peak temperature 48ºC for the open sun drying; the percentage mean moisture content is 31% as shown in Figs. 18 and 19, respectively. Through this, the solar dryer is confirmed to be a better dryer than the open sun drying technique for moisture removal in agricultural products.

3.3 Cost Analysis

The estimated cost for the economic solar grain dryer is shown in Table 1. The estimated cost for the materials used was about N17, 060.00.

Table 1 Cost analysis for construction of solar grain dryer

S/N	MATERIALS	DIMENSIONS	QUANTITY	UNIT PRICE (N)	TOTAL PRICE (N)
1	Transparent Glass	1250×900mm	1	2.400.00	2,400.00
2	Metal Sheet	850×750mm	1	2,000.00	2,000.00
3	Plywood (3/4” thick)	1000×1000mm	4	1,000.00	4,000.00
4	Wire Mesh	-	3yards	500.00	1,500.00
5	Nails	-	4kg	150.00	600.00

6	Hinges and Stapler	-	2	400.00	800.00
7	Black Paint		4litres	800.00	800.00
8	Brown Paint with Varnish		2 Seals	1,000.00	2,000.00
TOTAL					14,100.00

Contingency cost = 10% of material cost

= $10/100 \times 14100$

= N1,410.00

Labour cost = 10% of material cost + Contingency cost

= $10/100 \times (14100+1410)$

= $10/100 \times (15510)$

= N1551.00

Total Production Cost= Material Cost + Contingency Cost + Labour Cost

= 14100 + 1410 + 1551

= N17, 061.00

≈ N17, 060.00

4. CONCLUSIONS

An economic solar dryer for groundnut has been developed and its performance evaluation carried out in this study. The construction materials are locally sourced. The evaluation of the dryer in comparison with open sun drying indicated that average drying temperature of the drying cabinet was about $10^{o}C$ higher than the open sun drying justifying the additional heat received from direct solar radiation. It was observed that the drying temperature is at peak at about 1 pm. Percentage moisture content was faster using the solar dryer and the moisture level in the groundnut was brought to a safe level of 13% for storage purpose. The solar dryer gave better colour, aroma and cleaner look than the open sun drying, by physical examination. The dryer is economical in maintenance and will be suitable for usage by rural farmers to reduce wastes and to produce hygienic food that is void of contaminants. The dryer has safe operation and with a relatively higher efficiency when compared with open sun drying method.

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